Sawada *Economic Structures (2016) 5:11*
DOI 10.1186/s40008-016-0042-y

Journal of Economic Structures

RESEARCH Open Access

Effect of electricity system reform on retail electricity price increases in Japan

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Abstract

We examined the impact of the ongoing electricity system reform in Japan on social welfare, retail electricity service level and retail electricity prices. In our paper, the default system is monopolistic and combines average cost pricing with fixed entity profit, while the reformed system is characterized by competitive marginal cost pricing. We show that both social welfare and retail service efforts are improved after the electricity system reform. After considering the feedback from the wholesale electricity market, we also show that retail electricity liberalization does not always increase peak-time retail electricity price above the default price. Furthermore, we demonstrate that even where peak-time retail electricity price increases after electricity system reform, the magnitude of the price increase at peak periods is exceeded by that of the price drop in off-peak periods. Especially when the gap in electricity demand sizes between off-peak and peak is greater or when off-peak and peak periods are characterized by many low and few high demanders, the magnitude of the price increase in peak periods becomes still smaller. These results indicate that accurate evaluation of the impact of electricity system reform requires the incorporation of electricity related activities together in the same model.

Keywords: Electricity system reform in Japan, Retail electricity liberalization, Welfare analysis

1 Background

The Japanese government is conducting electricity system reform in stages and plans to complete this reform by 2020. Historically, all electricity related services in Japan have been overseen by regional monopolistic entities. After the reform is completed, both the wholesale and retail electricity markets will be perfectly competitive, as in most countries in the EU, and many states in the USA and Australia (METI 2015). For the most part, the wholesale electricity market in Japan has already been liberalized, whereas only high-voltage power in the retail electricity market has been liberalized. During the next several years, the scope of retail electricity liberalization is expected to expand to small-scale factories and households.

The liberalization of retail electricity is attracting considerable attention because of decreasing retail electricity prices and increasing electricity serving services. However, there are also some concerns that electricity system reform will increase peak-time electricity prices and corresponding tariffs as early electricity-liberalized countries.[1] Famously, the UK electricity market saw retail electricity prices double after liberalization. Should such price increases occur in Japan, they would become a heavy burden for small-scale factories and households. Our research question is straightforward. Could electricity system reform in Japan improve social welfare while reducing the cost of retail electricity? Even if improvement could be achieved, would this not be the result of someone's sacrifice?

In the economic literature, although there are various studies on the efficiency and design of the wholesale electricity market, there is little analytical research on the role of electricity retailers and the effects of retail electricity liberalization.[2] As far as we know, the only study on this area is Joskow and Tirole (2006). Joskow and Tirole (2006) examined the performances of the competitive real-time retail market given metering technology and consumer price responsiveness and showed that liberalization without the introduction of smart meters sometimes decreases the effectiveness of retail electricity trading. We applied their economic model to express electricity trading after the electricity system reform in Japan, but the aim of our study is quite different.

The remainder of this paper is organized as follows. First, we develop an economic model for a simple but complete electricity system. We use a full electricity related economic model, and thus this paper differs from most analytical studies on electricity trading that only focus on electricity related activities and omit many important properties for ease of analysis. Next, we characterize both the default and post-reform electricity systems in Japan. By comparing the performances of the two systems, we evaluate the impact of electricity system reform on social welfare, retail service efforts and retail electricity prices. We show that after the electricity system reform the peak-time retail electricity price could be higher, equal to or even lower than the default price. Including the case where system reform results in an electricity price drop, we show three cases where electricity system reform does not negatively impact small-scale factories and households. In concluding section, we summarize our findings.

2 Model

We consider a simple economy with one representative electricity generator, one representative retailer and final consumers $i = 1 \ldots n$. Electricity market is vertically separated, and both wholesale and retail electricity are traded in each market at each period $t = 1 \ldots T$. Following Joskow and Tirole (2006), we assume homogeneous consumers differing their demand size. Then, the electricity demand function is expressed by

$$q_{it} = \theta_{it} D\left(p_{it}^{r}\right), \quad Q_t = \sum_i q_{it}, \quad Q = \sum_i \sum_t q_{it}, \tag{1}$$

[1] Details and results of electricity system reforms in the UK, Norway, Alberta and California are summarized by Woo et al. (2003).

[2] Many studies on the wholesale electricity market compare two atypical auction systems, discriminatory and uniform price auction, which have been applied to wholesale electricity trading. Those studies are further classified based on whether they adopt discrete step function or continuous supply function equilibrium. Fabra et al. (2006) is a major study that adopted step function, while Genc (2009) and Genc and Reynols (2011) adopted supply function equilibrium. Expressing wholesale electricity auction by supply function equilibrium is often criticized for not reflecting realistic discrete trading. However, the gap between the discrete and continuous models is bridged by recent studies, most notably Holmberg et al. (2013).

where θ_{it} denotes the size of consumer i's demand for electricity at time t and $D(\cdot)$ is C^2, a decreasing and concave function. Q_t is the sum of total consumer demand at time t. Q is the total demand throughout the trading periods. The utility of consumer i from using electricity is $U(q_{it})$. We assume $U(\cdot)$ is C^2, an increasing and concave function.

A retailer purchases electricity on the wholesale market at price p_t^w and retails electricity to final consumers at price p_t^r. Retail service has retail cost $C(Q, e)$. We assume this retail cost increases with the total amount of traded electricity Q and that retailers can decrease this cost through retail service efforts e, that is, $C_Q > 0$ and $C_e < 0$. Also, retail service efforts cost $F(e)$ which is $F(0) = 0, C^2$, an increasing and convex function.

Normally, supply function of wholesale electricity should be derived from the generator's profit maximization condition that marginal generation cost equals to the wholesale price. However, to focus on the retail market analysis, we do not explicitly solve the generator's problem but directly assume that the supply function of wholesale electricity is increasing function of wholesale price and expressed by $S(p_t^w)$. Therefore, the role of a generator here is to supply electricity according to the wholesale price. The wholesale price is determined by the market clearing condition of the wholesale electricity market at each trading period:

$$Q_t = S\left(p_t^w\right). \tag{2}$$

Finally, we assume that the information on firms' cost is known to public and no issue of information asymmetry aries.

From the above settings, social welfare maximization is expressed by the following problem:

$$\max_{\{p_t^r \forall t \text{ and } e\}} \left\{ \sum_i \sum_t \left(p_t^r - p_t^w\right) q_{it} + \sum_i \sum_t \left(U(q_{it}) - p_t^r q_{it}\right) - C(Q,e) - F(e) \right\}. \tag{3}$$

This can be rearranged as follows:

$$\max_{\{p_t^r \forall t \text{ and } e\}} \left\{ \sum_i \sum_t \left(U(q_{it}) - p_t^w q_{it}\right) - C(Q,e) - F(e) \right\}. \tag{4}$$

The FOCs of this problem are

$$U' = p_t^w + C_Q \quad \forall t, \tag{5}$$

$$-C_e = F_e. \tag{6}$$

Eq. (5) implies that marginal utility equals marginal retail cost and Eq. (6) implies marginal reduction of retail service cost equals its marginal cost. Social optimum equilibrium, denoted as $(p_t^{ro}, p_t^{wo}, q_{it}^o, e^o)\ \forall i, t$, is obtained from Eqs. (1), (2), (5) and (6).

3 Characterization of two systems

3.1 Electricity trading under the default system

In this section, we characterize electricity trading under both the default system and the reformed system. In the default system, electricity is provided by a single monopolistic retailer. However, because of the public nature of the monopolistic retailer, its profits are restricted by law in Japan to a given level. We denote the given restricted profit level by $\bar{\pi}$. Moreover, because regulator prohibits a retailer from applying dynamic pricing such as time-of-use pricing, real-time pricing and critical peak pricing, charges for the electricity load are calculated with the single price p^r for every trading period. Then the retailer chooses p^r and e to satisfy

$$\sum_i \sum_t \left\{ \left(p^r - p_t^w \right) q_{it} \right\} - C(Q,e) - F(e) = \bar{\pi}. \tag{7}$$

Then the retail price is expressed by

$$p^r = \overline{p}^w + \frac{\bar{\pi} + C(Q,e) + F(e)}{Q}, \tag{8}$$

where $\overline{p}^w$ implies the average wholesale price during all trading periods and is defined by

$$\overline{p}^w := \frac{\sum_i \sum_t p_t^w q_{it}}{Q} = \frac{\sum_t p_t^w Q_t}{Q}. \tag{9}$$

Under the default system, the retail price is determined by average cost pricing. As is often pointed out, this average pricing does not incentivize retailers to increase retail service efforts, because any cost reduction arising from their service effort is reflected in the average price, and profit remains unchanged. Then, retail price and corresponding electricity load are expressed by

$$p^r = \overline{p}^w + \frac{\bar{\pi} + C(Q,e)}{Q}, \quad q_{it} = \theta_{it} D(p^r) \quad \forall i, t. \tag{10}$$

All consumers face the same average price, calculated based on the average wholesale price and average retail cost independent of the trading period and their own demand sizes. Finally, the wholesale electricity price at t is determined by the market clearing condition for the wholesale electricity market:

$$Q_t = \sum_i q_{it} = S\left(p_t^w\right). \tag{11}$$

Based on the above, the default system equilibrium $(\hat{p}^r, \hat{p}_t^w, \hat{q}_{it}, \hat{e}) \forall i, t$, is determined from Eqs. (8)–(11).

3.2 Retail electricity liberalization

In this section, we characterize electricity trading after the completion of the electricity system reform. The post-reform retail market will be perfectly liberalized, and retailers will be able to price freely based on retail electricity load. Following Joskow and Tirole (2006), we characterize the problem of a retailer assuming perfect competition as profit maximization under the restriction of consumer reservation utility:

$$\max_{\{p_t^r \forall t \text{ and } e\}} \sum_i \sum_t \left(p_t^r - p_t^w \right) q_{it} - C(Q,e) - F(e) \tag{12}$$

s.t.

$$U(q_{it}) - p_t^r q_{it} \geq \bar{U} \quad \forall t, \tag{13}$$

where $\bar{U}$ is the reservation utility level. The retailer can freely determine p_t^r and e provided the consumer's utility does not become less than $\bar{U}$. If this constraint is violated, the consumer will buy their electricity from other retailers who offer electricity with a more attractive tariff. Because Eq. (13) is satisfied by equality at the optimum, the problem can be rearranged as

$$\max_{\{p_t^r \forall t \text{ and } e\}} \sum_i \sum_t \left(U(q_{it}) - \bar{U} - p_t^w q_{it} \right) - C(Q, e) - F(e). \tag{14}$$

The FOCs of this problem are

$$U' = p_t^w + C_Q \quad \forall t, \tag{15}$$

$$-C_e = F_e. \tag{16}$$

Consumers determine the electricity load so as to satisfy the condition that the marginal utility equals the electricity price, that is, $U' = p_t^r$. Then, the equilibrium price and corresponding electricity load are

$$p_t^r = p_t^w + C_Q, \quad q_{it} = \theta_{it} D\left(p_t^r\right). \tag{17}$$

Firms in competitive market do not have an incentive to discriminate a retail price depending on consumer demand size, because price discrimination will give arbitrage opportunities to other retailers. Finally, the wholesale electricity price at time t is determined by the market clearing condition for the wholesale electricity market. The reformed system equilibrium denoted by $(p^{r*}, p_t^{w*}, q_{it}^*, e^*) \forall i, t$, is determined from Eqs. (11), (15)–(17) and is equivalent to the social optimum equilibrium. In contrast to the default system, the retail electricity price is determined by the marginal cost pricing and a retailer has an appropriate incentive to increase retail service efforts, thus maximizing social welfare.

Proposition 1 *Define the social welfare under the optimal situation, default system and reformed system by SW^o, $S\hat{W}$ and SW^*, respectively. Then it holds that $S\hat{W} \leq SW^* = SW^o$. Electricity system reform improves social welfare and can attain social optimality.*

4 Comparison of retail prices under two systems

4.1 Model specification

In this section, we specify our model to compare the results under two systems in detail. First, throughout the following analysis, we only consider two consumers $i = 1, 2$ with different demand sizes, given zero reservation utility and two trading periods, off-peak and peak, $t =$ off, peak. Second, we assume that retailers earn zero profit under the default system or $\bar{\pi} = 0$. Third, we specify the wholesale electricity supply function and retail electricity demand function by the following linear function:

$$S\left(p_t^w\right) = \alpha p_t^w, \tag{18}$$

$$D\left(p_t^r\right) = b - a p_t^r. \tag{19}$$

We also specify the retail service cost function by

$$C(Q, e) = \frac{Q^2}{(1+e)}. \tag{20}$$

Based on the specifications, the solutions of the two systems can be expressed by the following:[3]

$$\hat{p}^r = \frac{1}{\alpha \hat{Q}} \sum_t \hat{Q}_t^2 + \hat{Q}, \quad \hat{q}_{it} = \theta_{it}(b - a\hat{p}^r), \tag{21}$$

$$p_t^{r*} = \frac{Q_t^*}{\alpha} + \frac{2Q^*}{(1+e^*)}, \quad q_{it}^* = \theta_{it}(b - a p_t^{r*}). \tag{22}$$

Finally, to make our results more impressive, we further add the following Assumption 1 and Assumption 2.

Assumption 1 The level of retail service effort before the electricity reform is zero, $\hat{e} = 0$, while after the reform the level is infinitely large, $e^* = \infty$; i.e., cost efficiency in the retail electricity business improves considerably following the electricity system reform.

This assumption implies that we consider the most pessimistic situation under the default system where no retail service efforts are chosen and the most optimistic situation under the reformed system where significant service improvement is realized by the electricity system reform.

Because retailer profit is fixed under the default system, the retailer has little interest in retail service effort. In fact, for our economic model, any level of retail service effort can be a candidate for the equilibrium. To simplify our analysis, we normalize retail effort service under the default system to zero.

On the other hand, retail service effort after the electricity reform, e^*, is determined by the condition Eq. (16). The more effective the efforts or the lower their marginal cost, the greater the level of effort after the electricity system reform. By normalizing $\hat{e} = 0$, the magnitude of e^* itself implies the magnitude of efficiency gain realized by the electricity system reform and infinitely large e^* implies that significant service improvement is brought by the liberalization.

Assumption 2 The parameter set of the demand size for electricity consumption is either of the following *low demand dominant* or *high demand dominant*:

$$\textbf{Low Demand Dominant} \quad \overline{\theta} := \theta_{1\text{peak}} > \theta_{1\text{off}} = \theta_{2\text{peak}} = \theta_{2\text{off}} := \underline{\theta} \tag{23}$$

[3] See “Appendix 1” for a detailed derivation.

$$\textbf{High Demand Dominant} \quad \overline{\theta} := \theta_{1\text{peak}} = \theta_{1\text{off}} = \theta_{2\text{peak}} > \theta_{2\text{off}} := \underline{\theta} \tag{24}$$

Eq. (23) implies that off-peak and peak demand result from situations of many low demanders and few high demanders, respectively, while Eq. (24) implies that off-peak and peak demand result from situations of many high demanders and fewer low demanders, respectively. In both cases in Assumption 2, the following relationships are satisfied:

$$\theta_{1\text{off}} + \theta_{2\text{off}} < \theta_{1\text{peak}} + \theta_{2\text{peak}}, \tag{25}$$

$$\theta_{1\text{off}} + \theta_{1\text{peak}} > \theta_{2\text{off}} + \theta_{2\text{peak}}. \tag{26}$$

Eq. (25) implies that peak-time retail electricity demand exceeds off-peak demand, and Eq. (26) implies that consumer 1 has a larger demand size for electricity use than consumer 2.

4.2 Retail electricity price change with *low demand dominant*

Now, let us examine the changes brought by the electricity system reform in detail. Through Proposition 1, we show that the electricity system reform can improve social welfare, but how does the reform change electricity retail prices? Let us examine the magnitude of the relationship between p_t^{r*} and $\hat{p}^r$. Given Eqs. (21) and (22) with *low demand dominant*, then

$$\hat{p}^{rL} = \frac{b\Phi}{(1 + a\Phi)}, \tag{27}$$

$$p_{\text{off}}^{r*L} = \frac{2b\underline{\theta}}{\alpha}\left(1 + \frac{2a\underline{\theta}}{\alpha}\right)^{-1}, \tag{28}$$

$$p_{\text{peak}}^{r*L} = \frac{b(\overline{\theta} + \underline{\theta})}{\alpha}\left[1 + \frac{a(\overline{\theta} + \underline{\theta})}{\alpha}\right]^{-1}, \tag{29}$$

where Φ^L is defined by

$$\Phi^L := \left(1 + \frac{1}{\alpha}\right)(\overline{\theta} + 3\underline{\theta}) - \frac{4\underline{\theta}(\overline{\theta} + \underline{\theta})}{\alpha(\overline{\theta} + 3\underline{\theta})}. \tag{30}$$

By comparing Eqs. (27), (28) and (29), we obtain the following proposition.[4]

Proposition 2 *If α is sufficiently large, then $\hat{p}^{rL}$ becomes higher than p_{peak}^{r*L} and $p_{\text{off}}^{r*L} < p_{\text{peak}}^{r*L} < \hat{p}^{rL}$ is satisfied. And if α is small enough, then $\hat{p}^{rL}$ becomes never lower than p_{off}^{r*L} and $p_{\text{off}}^{r*L} < \hat{p}^{rL} < p_{\text{peak}}^{r*L}$ is satisfied.*

[4] See "Appendix 2" for proof in detail.

The order of equilibrium prices depends on the slope of the wholesale electricity supply function. This point is very important, because it implies the order of equilibrium of retail electricity prices is not determined within the retail electricity market itself. Thus, when trying to focus on retail electricity price change in the retail market, we must pay attention to the states of both the wholesale and retail markets.

The proposition includes the result where the equilibrium peak-time retail electricity price becomes lower than the default price. Why should such a result occur? Larger α implies the wholesale electricity supply function is relatively flat. Remember that the retail electricity price depends on two factors, wholesale electricity price as a cost component and marginal retail service cost. While the wholesale electricity price becomes almost constant because of its flat supply function, marginal retail service cost diminished significantly after the system reform. The default retail electricity price could become higher for the remaining retail service cost. This is why the peak-time price becomes lower than the default price.

If α is small and the wholesale electricity supply function is relatively steep, the peak-time retail electricity price becomes higher than the default price. Rather, in this case, we immediately have the following corollary that could allay some of the anxiety about the burden from heavy electricity tariffs.

Corollary 1 *It holds that* $|p^{r*L}_{\text{off}} - \hat{p}^{rL}| > |p^{r*L}_{\text{peak}} - \hat{p}^{rL}|$. *That is, the absolute difference between the equilibrium peak-time retail electricity price and the default price is lower than for the off-peak price and the default price. Moreover, as the gap between* $\underline{\theta}$ *and* $\overline{\theta}$ *increases, so too does the magnitude of* $|p^{r*L}_{\text{off}} - \hat{p}^{rL}| - |p^{r*L}_{\text{peak}} - \hat{p}^{rL}|$.

Clearly the peak-time retail electricity price rises after the system reform, but the impact of the reform in causing a drop in the off-peak retail price is more significant than its influence on peak-time prices. That is, the price gap between the off-peak and peak periods is not determined by the price rise but mainly by the price drop. This tendency strengthens as the gap between demand sizes enlarges. Higher peak-time demand increases the gap between off-peak and peak-time demand. Therefore, higher peak-time demand is sometimes preferable and results in lower peak-time retail electricity price.

4.3 Retail electricity price change with *high demand dominant*

Similarly, we look at the relationship between price change and the magnitude of the relationship between p^{r*}_t and $\hat{p}^r$, with *high demand dominant*. Under assumptions, Eqs. (21) and (22) become

$$\hat{p}^{rH} = \frac{b\Phi^H}{(1 + a\Phi^H)}, \tag{31}$$

$$p^{r*H}_{\text{off}} = \frac{b(\overline{\theta} + \underline{\theta})}{\alpha}\left(1 + \frac{a(\overline{\theta} + \underline{\theta})}{\alpha}\right)^{-1}, \tag{32}$$

$$p^{r*H}_{\text{peak}} = \frac{2b\overline{\theta}}{\alpha}\left(1 + \frac{2a\overline{\theta}}{\alpha}\right)^{-1}, \tag{33}$$

where Φ^H is defined by

$$\Phi^H := \left(1+\frac{1}{\alpha}\right)(3\overline{\theta}+\underline{\theta}) - \frac{4\overline{\theta}(\overline{\theta}+\underline{\theta})}{\alpha(3\overline{\theta}+\underline{\theta})}. \tag{34}$$

By comparing Eqs. (31), (32) and (33), we have the following proposition and corollary, just as in the previous section.[5]

Proposition 3 *If α is large enough, then $\hat{p}^{rH}$ becomes higher than p^{r*H}_{peak} and $p^{r*H}_{\text{off}} < p^{r*H}_{\text{peak}} < \hat{p}^{rH}$ is satisfied. And if α is small enough, then $\hat{p}^{rH}$ never becomes lower than p^{r*H}_{off} and $p^{r*H}_{\text{off}} < \hat{p}^{rH} < p^{r*H}_{\text{peak}}$ is satisfied.*

Corollary 2 *It holds that $|p^{r*H}_{\text{off}} - \hat{p}^{rH}| > |p^{r*H}_{\text{peak}} - \hat{p}^{rH}|$. That is, the absolute value of the difference between the equilibrium peak-time retail electricity price and the default price is lower than that of the difference between the off-peak price and the default price. Moreover, as the gap between $\underline{\theta}$ and $\overline{\theta}$ becomes greater, so too does the magnitude of $|p^{r*H}_{\text{off}} - \hat{p}^{rH}| - |p^{r*H}_{\text{peak}} - \hat{p}^{rH}|$.*

Although most of the results remain unchanged from the previous section, by combining the above propositions and corollaries, we finally have the following proposition that explains how the two parameter sets of the demand size for electricity consumption, *low demand dominant* and *high demand dominant*, differently affect the price change.[6]

Proposition 4 *It holds that $|p^{rL}_{\text{off}} - \hat{p}^{rL}| - |p^{rL}_{\text{peak}} - \hat{p}^{rL}| > |p^{rH}_{\text{off}} - \hat{p}^{rH}| - |p^{rH}_{\text{peak}} - \hat{p}^{rH}|$. That is, the peak-time impact is higher in the high demand dominant scenario than the low demand dominant scenario.*

Therefore, if the peak-time demand is formed by high demanders, that is, if most consumers use electricity a lot, then the impact of the peak-time demand becomes much more significant. This result alone is not surprising, but as summarized in concluding section, when combined with the two previous corollaries, it becomes highly suggestive. Whether peak-time retail electricity price negatively affects some economic agents depends not only on the demand size gap, $\overline{\theta} - \underline{\theta}$, but also on how the off-peak and peak-time demand are constituted.

5 Concluding remarks

In this paper, we examined the retail electricity price change resulting from the current electricity system reform in Japan. We characterize the default electricity system as based on average pricing and the reformed electricity system as based on marginal pricing. Moreover, to sharpen our analysis, we specified some functions and only compared the most pessimistic case under the default system with the most optimistic case under the reformed system.

Contrary to the ex-ante anxiety about retail electricity price increases, we have three results that show no serious consequences from the peak-time retail electricity price

[5] See "Appendix 3" for detailed proof.

[6] See "Appendix 3" for detailed proof.

after the electricity system reform. First, if the wholesale electricity supply function is flat, then the peak-time electricity price could become even lower than the default price. This result indicates that even if the target of the analysis is only electricity related activities (e.g., trading in the retail electricity market), we should use the model that contains all the electricity related activities (whether occurring in the retail electricity market or the wholesale electricity market). Analysis with the economic model focusing only on certain electricity related activities might miss important properties and yield misleading results.

Second, we showed that even if the wholesale supply function is steep and the peak-time retail electricity price exceeds that in the default system, the magnitude of the price rise is exceeded by that of the price drop in the off-peak periods. Thus, the price gap between the off-peak and peak periods after the electricity system reform results mostly from the drop of the off-peak electricity price. Moreover, we also showed that the magnitude of the peak-time price rise decreases as people use more electricity in the peak period.

Finally, we showed that the impact of the reform on the peak-time price also depends on how the peak-time itself is constituted, that is, *low demand dominant* or *high demand dominant*. If the peak periods are characterized not by many high demanders and few low demanders but by many low demanders and few high demanders, then the price rise in the peak periods will become smaller. This seems inconsistent with the second result, but the second result is obtained from the difference in the demand sizes of individual consumers, while the third result is obtained from the difference in overall trends in electricity use. We must carefully distinguish the effects of these two different forms of electricity consumption.

One lesson from the experiences of early retail electricity-liberalized countries is that liberalization does not always quickly provide competition, and its impacts differ depending on country-specific default system. For example, many consumers retained their default contracts in Denmark, while in other Nordic countries a switch to reformed contracts proceeded smoothly (Johnsen and Olsen 2011). In that sense, our analysis has some problems owing to the assumption of perfect competition after the electricity system reform. To make our analysis more realistic would require not just comparing the two extremes, but precisely examining the process of change. The lesson also indicates that our analysis could be expanded to similar target-planned electricity system reform in many other countries. Major results obtained from applying our framework must change if supposing a country-specific default system in other countries. These interesting expansions are left for future studies.

Acknowledgements
This work was supported by CREST, JST.

Appendix 1: Derivation of equilibrium price in the specified model

According to the specification, the marginal retail cost, average retail cost and electricity load are $C_Q = \frac{2Q}{(1+e)}, \frac{C(Q,e)}{Q} = \frac{Q}{(1+e)}$ and $\hat{q}_{it} = \theta_{it}(b - a\hat{p}^r)$. By the wholesale market clearing condition, $Q_t = \alpha p_t^w$, we have $p_t^w = \frac{Q_t}{\alpha}$. Then, by the zero profit condition or $\bar{\pi} = 0$, we have the following retail electricity price under the default system:

$$\hat{p}^r = \frac{\sum_i \sum_t \hat{p}_t^w \hat{q}_{it}}{\hat{Q}} + \frac{C(\hat{Q}, \hat{e})}{\hat{Q}} = \frac{1}{\alpha \hat{Q}} \sum_t \hat{Q}_t^2 + \hat{Q} = \left(1 + \frac{1}{\alpha}\right)\hat{Q} - \frac{2\hat{Q}_{\text{off}}\hat{Q}_{\text{peak}}}{\alpha \hat{Q}}. \tag{35}$$

Corresponding $\hat{Q}_{\text{off}}$ and $\hat{Q}_{\text{peak}}$ with *low demand dominant* are

$$\hat{Q}_{\text{off}}^L = (\theta_{1\text{off}} + \theta_{2\text{off}})(b - a\hat{p}^r) = 2\underline{\theta}(b - a\hat{p}^r), \tag{36}$$

$$\hat{Q}_{\text{peak}}^L = (\theta_{1\text{peak}} + \theta_{2\text{peak}})(b - a\hat{p}^r) = (\overline{\theta} + \underline{\theta})(b - a\hat{p}^r). \tag{37}$$

By Eqs. (36) and (37), Eq. (35) can be further rearranged as follows:

$$\hat{p}^r = (b - a\hat{p}^r)\left[\left(1 + \frac{1}{\alpha}\right)(\overline{\theta} + 3\underline{\theta}) - \frac{4\underline{\theta}(\overline{\theta} + \underline{\theta})}{\alpha(\overline{\theta} + 3\underline{\theta})}\right]. \tag{38}$$

By solving Eq. (38) with respect to $\hat{p}^r$, we have the equilibrium retail electricity price under the default system with *low demand dominant* denoted by $\hat{p}^{rL}$:

$$\hat{p}^{rL} = \frac{b\Phi^L}{(1 + a\Phi^L)}, \tag{39}$$

where Φ^L is defined by

$$\Phi^L := \left(1 + \frac{1}{\alpha}\right)(\overline{\theta} + 3\underline{\theta}) - \frac{4\underline{\theta}(\overline{\theta} + \underline{\theta})}{\alpha(\overline{\theta} + 3\underline{\theta})}. \tag{40}$$

Similarly, $\hat{Q}_{\text{off}}$ and $\hat{Q}_{\text{peak}}$ with *high demand dominant* are

$$\hat{Q}_{\text{off}}^H = (\theta_{1\text{off}} + \theta_{2\text{off}})(b - a\hat{p}^r) = (\overline{\theta} + \underline{\theta})(b - a\hat{p}^r), \tag{41}$$

$$\hat{Q}_{\text{peak}}^H = (\theta_{1\text{peak}} + \theta_{2\text{peak}})(b - a\hat{p}^r) = 2\overline{\theta}(b - a\hat{p}^r). \tag{42}$$

And the equilibrium retail electricity price under the default system with *high demand dominant* denoted by $\hat{p}^{rH}$ is

$$\hat{p}^{rH} = \frac{b\Phi^H}{(1 + a\Phi^H)}, \tag{43}$$

where Φ^H is defined by

$$\Phi^H := \left(1 + \frac{1}{\alpha}\right)(3\overline{\theta} + \underline{\theta}) - \frac{4\overline{\theta}(\overline{\theta} + \underline{\theta})}{\alpha(3\overline{\theta} + \underline{\theta})}. \tag{44}$$

Next, let us derive the equilibrium retail electricity price under the reformed system. Based on the model specification and assumptions, the retail electricity price under the reformed system is

$$p_t^{r*} = p_t^{w*} + C_Q|_{Q=Q^*, e=e^*} = \frac{Q_t^*}{\alpha} + \frac{2Q^*}{(1 + e^*)} \quad \text{for } t = \text{ peak, off}. \tag{45}$$

Because we only consider the most optimistic case with $e^* = \infty$ by Assumption 1,

$$p_t^{r*} = \frac{Q_t^*}{\alpha} \text{ for } t = \text{ peak, off}. \tag{46}$$

Corresponding Q_{off}^* and Q_{peak}^* with *low demand dominant* are

$$Q_{\text{off}}^* = \theta_{1\text{off}}\left(b - ap_{1\text{off}}^{r*}\right) + \theta_{2\text{off}}\left(b - ap_{2\text{off}}^{r*}\right) = 2\underline{\theta}\left(b - ap_{\text{off}}^{r*}\right), \tag{47}$$

$$Q_{\text{peak}}^* = \theta_{1\text{peak}}\left(b - ap_{1\text{peak}}^{r*}\right) + \theta_{2\text{peak}}\left(b - ap_{2\text{peak}}^{r*}\right) = (\overline{\theta} + \underline{\theta})\left(b - ap_{\text{peak}}^{r*}\right). \tag{48}$$

By using Eqs. (46), (47) and (48), we have the following equilibrium retail electricity prices under the reformed system with *low demand dominant* denoted by p_{off}^{r*L} and p_{peak}^{r*L}:

$$p_{\text{off}}^{r*L} = \frac{2\underline{\theta}}{\alpha} b\left(1 + \frac{2\underline{\theta}}{\alpha} a\right)^{-1}, \tag{49}$$

$$p_{\text{peak}}^{r*L} = \frac{(\overline{\theta} + \underline{\theta})}{\alpha} b\left(1 + \frac{(\overline{\theta} + \underline{\theta})}{\alpha} a\right)^{-1}. \tag{50}$$

Similarly, we can easily obtain the equilibrium retail electricity price under the reformed system with *high demand dominant* denoted by p_{off}^{r*H} and p_{peak}^{r*H}, as follows:

$$p_{\text{off}}^{r*H} = \frac{(\overline{\theta} + \underline{\theta})}{\alpha} b\left(1 + \frac{(\overline{\theta} + \underline{\theta})}{\alpha} a\right)^{-1}, \tag{51}$$

$$p_{\text{peak}}^{r*H} = \frac{2\overline{\theta}}{\alpha} b\left(1 + \frac{2\overline{\theta}}{\alpha} a\right)^{-1}. \tag{52}$$

Appendix 2: Proof of Proposition 2 and Corollary 1

Here, we show the magnitude of the relationship among equilibrium prices derived in the previous section. Notice that all equilibrium prices derived as Eqs. (38), (43) and (49)–(52) can be expressed in the form, $\frac{bX}{1+aX}$. If $X = \Phi^L, \Phi^H, \frac{2\underline{\theta}}{\alpha}, \frac{(\overline{\theta}+\overline{\theta})}{\alpha}, \frac{(\overline{\theta}+\underline{\theta})}{\alpha}$ and $\frac{2\theta}{\alpha}$, then $\frac{bX}{1+aX}$ becomes $\hat{p}^{rL}$, $\hat{p}^{rH}$, p_{off}^{r*L}, p_{peak}^{r*L}, p_{off}^{r*H} and p_{peak}^{r*H} , respectively. The difference of $\frac{bX}{1+aX}$ with some constants $X = X_1$ and X_2 is

$$\frac{bX_1}{1 + aX_1} - \frac{bX_2}{1 + aX_2} = \frac{b(X_1 - X_2)}{(1 + aX_1)(1 + aX_2)}. \tag{53}$$

Therefore,

$$X_1 \gtreqless X_2 \Leftrightarrow \frac{bX_1}{1 + aX_1} \gtrless \frac{bX_2}{1 + aX_2}. \tag{54}$$

Moreover, the magnitude of difference is proportional to the difference between X_1 and X_2. Eqs. (53) and (54) implies that we only compare the magnitude of the relationships among Φ^L, Φ^H, $\frac{2\underline{\theta}}{\alpha}$, $\frac{(\underline{\theta}+\overline{\theta})}{\alpha}$, $\frac{(\overline{\theta}+\underline{\theta})}{\alpha}$ and $\frac{2\theta}{\alpha}$ to derive the magnitudes of the relationships among equilibrium prices and of the differences among them.

In this section, we consider the case with *low demand dominant*, that is, Φ^L, $\frac{2\underline{\theta}}{\alpha}$ and $\frac{(\underline{\theta}+\overline{\theta})}{\alpha}$. Again notice that Φ^L can be rearranged by $\Phi^L = \frac{1}{\alpha}\left[\alpha(\overline{\theta}+3\underline{\theta}) + (\overline{\theta}+3\underline{\theta}) - \frac{4\underline{\theta}(\overline{\theta}+\underline{\theta})}{\overline{\theta}+3\underline{\theta}}\right]$, then we can omit $\frac{1}{\alpha}$ to examine the order. If α takes an infinitely large value, then $2\underline{\theta} > (\overline{\theta}+\underline{\theta}) > \alpha(\overline{\theta}+3\underline{\theta}) + (\overline{\theta}+3\underline{\theta}) - \frac{4\underline{\theta}(\overline{\theta}+\underline{\theta})}{\overline{\theta}+3\underline{\theta}}$ holds and therefore

$$p_{\text{off}}^{r*L} < p_{\text{peak}}^{r*L} < \hat{p}^{rL}. \tag{55}$$

And if α takes a value of near zero, then it holds that $2\underline{\theta} < \left[(\overline{\theta}+3\underline{\theta}) - \frac{4\underline{\theta}(\overline{\theta}+\underline{\theta})}{\overline{\theta}+3\underline{\theta}}\right] < (\overline{\theta}+\underline{\theta})$, because $\left[(\overline{\theta}+3\underline{\theta}) - \frac{4\underline{\theta}(\overline{\theta}+\underline{\theta})}{\overline{\theta}+3\underline{\theta}}\right] - 2\underline{\theta} = \frac{\overline{\theta}^2-\underline{\theta}^2}{\overline{\theta}+3\underline{\theta}} > 0$ and $(\overline{\theta}+\underline{\theta}) - \left[(\overline{\theta}+3\underline{\theta}) - \frac{4\underline{\theta}(\overline{\theta}+\underline{\theta})}{\overline{\theta}+3\underline{\theta}}\right] = 2\left(\frac{\overline{\theta}\underline{\theta}-\underline{\theta}^2}{\overline{\theta}+3\underline{\theta}}\right) > 0$. Therefore,

$$p_{\text{off}}^{r*L} < \hat{p}^{rL} < p_{\text{peak}}^{r*L}. \tag{56}$$

Finally, the difference in magnitude between the off-peak price drop and the peak-time price increase is

$$\frac{\overline{\theta}^2-\underline{\theta}^2}{\overline{\theta}+3\underline{\theta}} - \frac{2(\overline{\theta}\underline{\theta}-\underline{\theta}^2)}{\overline{\theta}+3\underline{\theta}} = \frac{(\overline{\theta}-\underline{\theta})^2}{\overline{\theta}+3\underline{\theta}} > 0 \Leftrightarrow \left|p_{\text{off}}^{r*L} - \hat{p}^{rL}\right| > \left|p_{\text{peak}}^{r*L} - \hat{p}^{rL}\right|. \tag{57}$$

Therefore, the price change in the off-peak period is more significant, and as the difference between demand sizes $(\overline{\theta}-\underline{\theta})$ increases, the off-peak impact considerably exceeds the peak-time impact.

Appendix 3: Proof of Proposition 3, Corollary 2 and Proposition 4

Next, let us consider the case with *high demand dominant*, that is, Φ^H, $\frac{2\overline{\theta}}{\alpha}$ and $\frac{(\overline{\theta}+\overline{\theta})}{\alpha}$. Most of the proof is the same as in the previous section. Φ^H can be rearranged by $\Phi^H = \frac{1}{\alpha}\left[\alpha(3\overline{\theta}+\underline{\theta}) + (3\overline{\theta}+\underline{\theta}) - \frac{4\overline{\theta}(\overline{\theta}+\underline{\theta})}{3\overline{\theta}+\underline{\theta}}\right]$. Thus we see the order of $\alpha(3\overline{\theta}+\underline{\theta}) + (3\overline{\theta}+\underline{\theta}) - \frac{4\overline{\theta}(\overline{\theta}+\underline{\theta})}{\overline{\theta}+3\underline{\theta}}$, $(\overline{\theta}+\underline{\theta})$ and $2\overline{\theta}$.

Again, if α takes an infinitely large value, then

$$p_{\text{off}}^{r*H} < p_{\text{peak}}^{r*H} < \hat{p}^{rH}. \tag{58}$$

And if α takes a value of near zero, then it holds that $(\overline{\theta}+\underline{\theta}) < \left[(3\overline{\theta}+\underline{\theta}) - \frac{4\overline{\theta}(\overline{\theta}+\underline{\theta})}{3\overline{\theta}+\underline{\theta}}\right] < 2\overline{\theta}$, because $\left[(3\overline{\theta}+\underline{\theta}) - \frac{4\overline{\theta}(\overline{\theta}+\underline{\theta})}{3\overline{\theta}+\underline{\theta}}\right] - (\overline{\theta}+\underline{\theta}) = 2\left(\frac{\overline{\theta}^2-\overline{\theta}\underline{\theta}}{3\overline{\theta}+\underline{\theta}}\right) > 0$ and $2\overline{\theta} - \left[(3\overline{\theta}+\underline{\theta}) - \frac{4\overline{\theta}(\overline{\theta}+\underline{\theta})}{3\overline{\theta}+\underline{\theta}}\right] = \frac{\overline{\theta}^2-\underline{\theta}^2}{3\overline{\theta}+\underline{\theta}} > 0$. Therefore,

$$p_{\text{off}}^{r*H} < \hat{p}^{rH} < p_{\text{peak}}^{r*H}. \tag{59}$$

The difference in magnitude between the off-peak price drop and the peak-time price increase is

$$\frac{\overline{\theta}^2-\underline{\theta}^2}{3\overline{\theta}+\underline{\theta}}-\frac{2(\overline{\theta}^2-\overline{\theta}\underline{\theta})}{3\overline{\theta}+\underline{\theta}}=\frac{(\overline{\theta}-\underline{\theta})^2}{3\overline{\theta}+\underline{\theta}}>0\Leftrightarrow\left|p_{\text{off}}^{r*H}-\hat{p}^{rH}\right|>\left|p_{\text{peak}}^{r*H}-\hat{p}^{rH}\right|. \tag{60}$$

Finally, from Eqs. (57) and (60) it holds that

$$\frac{(\overline{\theta}-\underline{\theta})^2}{\overline{\theta}+3\underline{\theta}}>\frac{(\overline{\theta}-\underline{\theta})^2}{3\overline{\theta}+\underline{\theta}}\Leftrightarrow\left|p_{\text{off}}^{r*L}-\hat{p}^{rL}\right|-\left|p_{\text{peak}}^{r*L}-\hat{p}^{rL}\right|>\left|p_{\text{off}}^{r*H}-\hat{p}^{rH}\right|-\left|p_{\text{peak}}^{r*H}-\hat{p}^{rH}\right|. \tag{61}$$

Therefore, the impact of the electricity system reform on the off-peak price is more significant in the *low demand dominant* scenario.

Received: 13 October 2015 Accepted: 17 March 2016
Published online: 31 March 2016

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